Report on field quality in the main LHC quadrupole collared coils and cold masses: August-September 2004

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This report gives data relative to field quality measured at room temperature in quadrupole collared coils and cold masses during the period August 1– September 30 2004, comparison to beam dynamics targets. Updated graphs can be found in the LHC-MMS field quality observatory http://lhc-div-mms.web.cern.ch/lhc-div-mms/MMSPAGES/MA/qobs.html.

EDMS n. 520634

The dashboard

- Available measurements: at room temperature we have 335 apertures (167.5 magnets) and 107 cold masses. At 1.9 K we have measurements of 12 quadrupoles (7 complete measurements plus 5 partial)[1].
- In these two months, 38 apertures (i.e., 19 equivalent quadrupoles) and 27 cold masses have been measured at room temperature, and 3 magnets at 1.9 K.

What's new

Issues critical for beam dynamics:

- **Spread of focusing strength:** already in room temperature data, the spread of focusing strength is 25% higher than target. This spread is not due to the mixing of different cross-sections, but rather to the collar permeability out of tolerance in the more recent production. The steps taken to solve the problem (control of the collar permeability and rejection of collar batches if the parameter is larger than 1.01) have been effective, and the spread is now critical, but under control (see pages 4-6).
- **Correlations for focusing strength and b6:** warm-cold offsets in the focusing strength are stable over the 10 available magnets), but the first measured value seems out of statistics. Warm-cold offsets for the integrated b6 are increasing from –4 to –3.5 units in the last 3 quadrupoles tested at 1.9 K (see pages 12-13).

Issues non-critical for beam dynamics:

- **Random b6:** is two times the target due to the mix of different cross-sections. An installation of homogeneous cross-sections in the same arc could cure the problem.
- **Systematic b4:** the non-zero systematic component seen at the beginning of the production is disappearing. Correlations to cold measurements are given in Section III.4.
- **Systematic a6:** there is a non-zero systematic component of a6 in all quadrupoles. Correlations to cold measurements are given in Section III.4.

CONTENTS

[1] These numbers refer to measurements carried out by AT-MTM at SM18, available in Oracle database. Measurements at Block4 are not included in the report.

PART I: MEASURED MAGNETS AND ASSEMBLY DATA

- 38 new apertures (i.e. 19 equivalent quadrupoles) and 27 cold masses have been measured at room temperature (see Fig. 1).

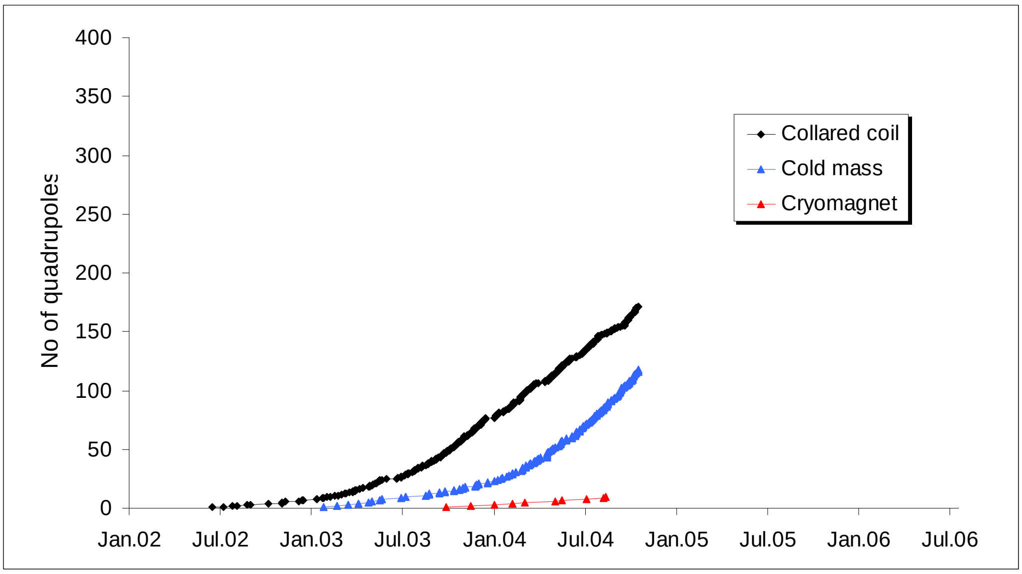

Fig. 1: Number of magnets measured at the manufacturers at room temperature at different stages of assembly procedure

- Cross-section: all apertures have X-section 2.
- Coil protection sheet[2]: all apertures have a coil protection sheet of 0.87 mm, with the exception of aperture 304 and 305 (0.95 mm).

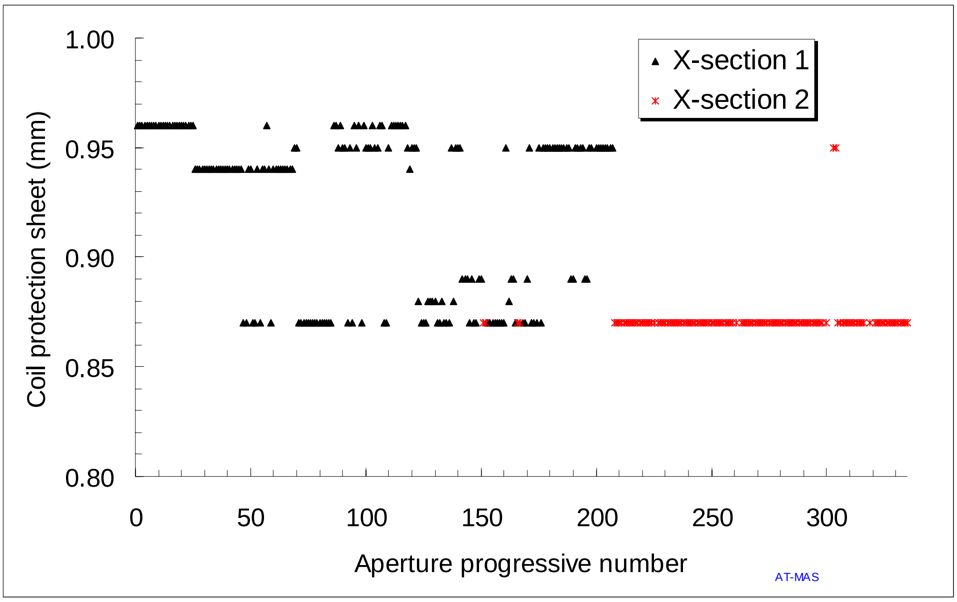

Fig. 2: Thickness of the coil protection sheet used in the apertures, separated according to different cross-sections.

[2] The coil protection sheet is a stainless steel sheet between the collar poles and the coils (covering both inner and outer layer) that can be used to optimize pre-stress or field quality.

PART II: MEASUREMENTS VERSUS BEAM DYNAMICS TARGETS

- Best estimates of normal and skew systematic components are given in Fig. 3. All the multipoles are within specifications, with the exception of b6.
- For b6, the average is carried out over 202 of magnets with X-section 1 and 133 of X-section 2: this gives a systematic b6 of 0.3 units larger than the targets. When the contribution of the different X-sections is separated, one finds that b6 in X-section 1 is 1.5 units larger than the upper target, and that in X-section 2 it is well centred in the allowed range (see Fig. 3, left).
- Details on trends are given in Part III.

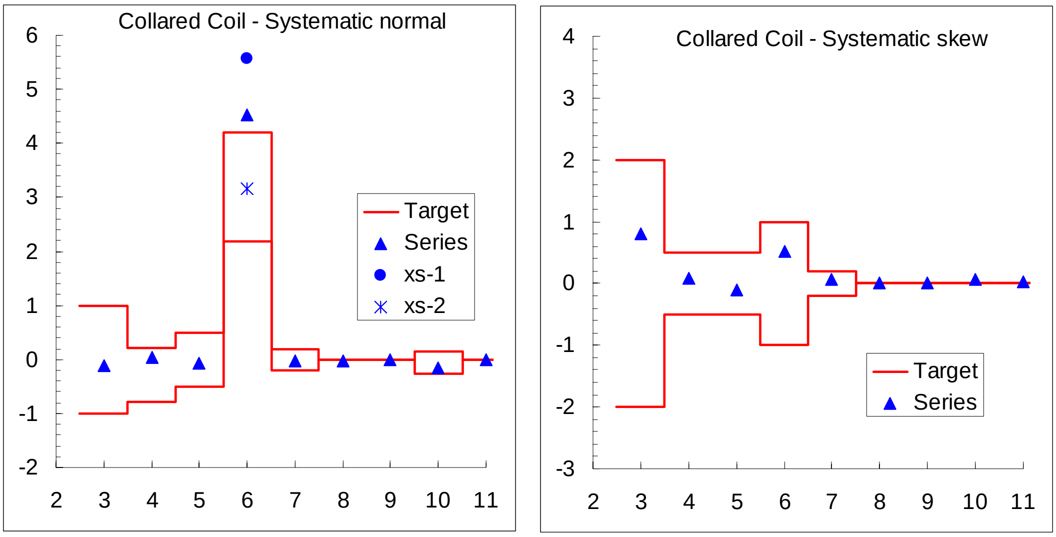

Fig. 3: Best estimate for systematic normal (left) and skew (right) multipoles versus beam dynamics limits (red line).

- Best estimate of the random component is given in Fig. 4. All values are within targets with the exception of b2 and b6.
- The standard deviation of b2 (integrated field gradient) is 12.5 units, i.e. 25% more than the upper limit of 10 units. This target is a hard limit, which is established on the budget allocated for beta beating. The large measured spread is not given by the mixing of the two different cross-sections. The situation for X-section 1 was at the limit of the specification, the spread being of 11.3 units. The situation is worse for X-section 2, where the spread is of 13.3 units. Most of this spread is due to the variations in collar permeability (see previous report) that are now well under control. Therefore, the spread in focusing strength should decrease in the future. Warm to cold correlations are adding a non-negligible contribution to the spread.
- The spread of b6 over all apertures (1.4 units) is mainly due to the mixing of the two different X-sections. Data of X-section 1 have a spread of 0.7 units, and one has a similar value for X-section 2, i.e. within targets. Indeed, the target for beam dynamics on random b6 is not a hard limit.

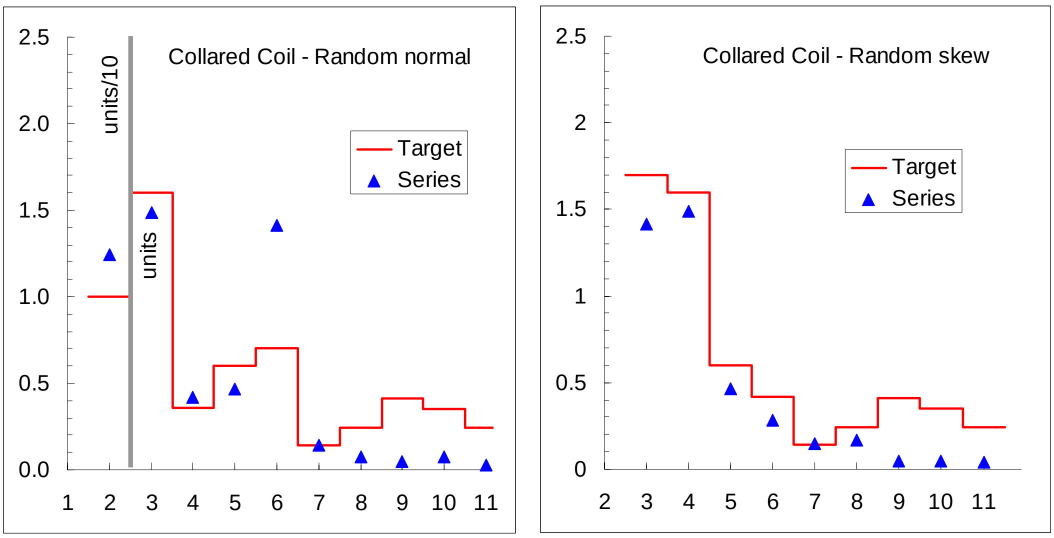

Fig. 4: Best estimate for random normal (left) and skew (right) component in the measured collared coils compared to targets for random at 1.9 K.

PART III: TRENDS IN FIELD QUALITY

3.1 Trends in focusing strength

3.1.1 Trends in magnetic length

- Magnetic length of the aperture is extremely stable (within ±5 units). A small increase of both the systematic and the random have been observed in the last 80 apertures. The standard deviation over all apertures is indeed very small (2.0 units).

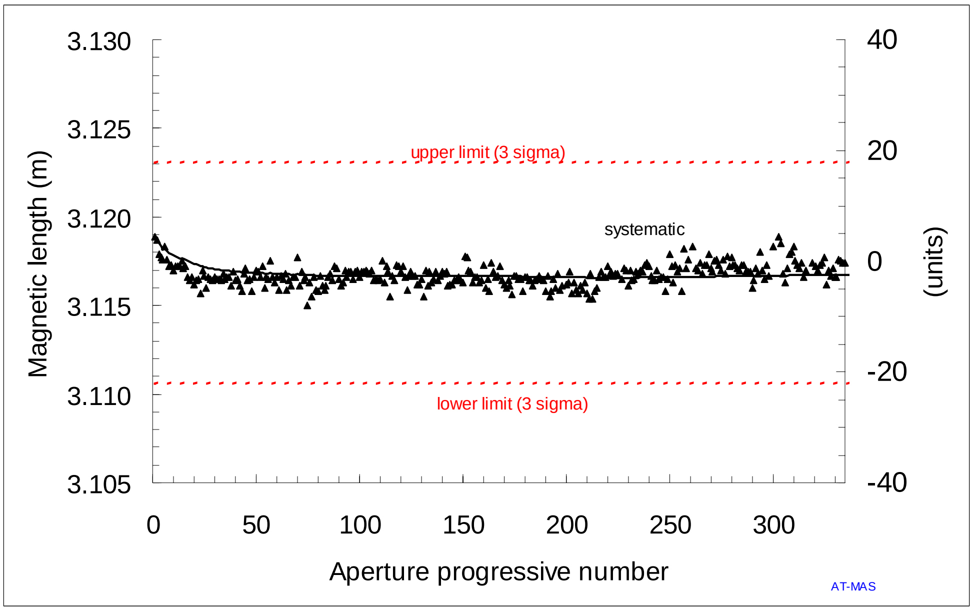

Fig. 5: Magnetic length of the measured collared coils (dots) and running average (solid line).

- Magnetic length of **cold masses** is also extremely stable (see Fig. 6)[3]. The standard deviation over all cold masses is 1.5 units.

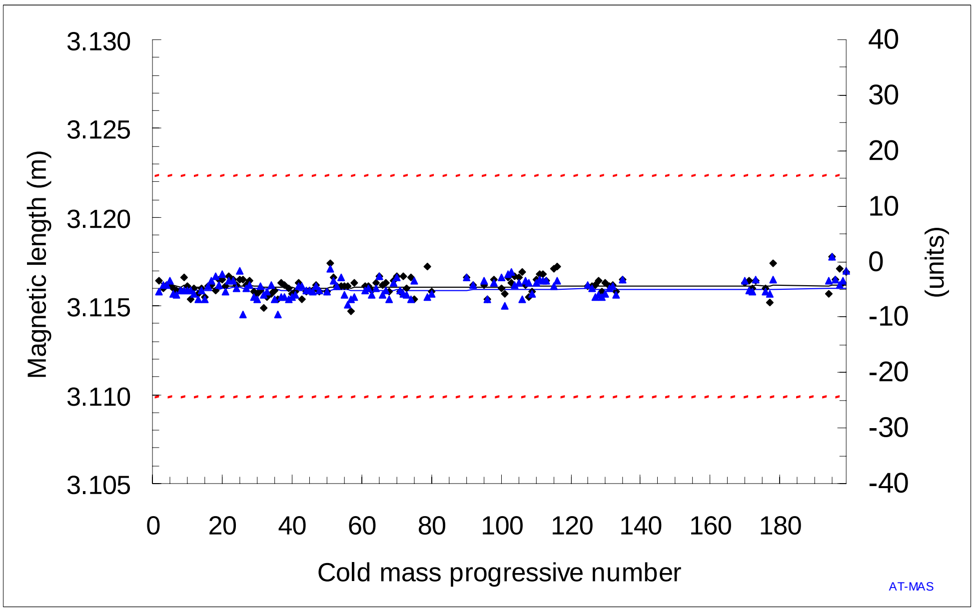

Fig. 6: Magnetic length of the measured **cold masses** (black dots Aperture1, blue dots Aperture 2) and running average (solid line).

[3] Please note that the ordering of the apertures is not the same of the ordering of the cold masses. Therefore, the trends in plots of Figs. 5-6, 7-8 and 9-10 are not directly comparable. The two apertures that compose a cold mass are chosen according to a matching criteria developed by CEA.

3.1.2 Trends in field gradient

- The spread of the field gradient in the straight part of the magnet is large (see Fig. 7). A drop of around 20 units has been seen after aperture 140, with the introduction of X-section 2, against an expected value of 6 units. An increase of around 10 units has been seen after aperture 240, traced back to a significant out of tolerance of collar permeability. Now this parameter is carefully monitored, and collar batches with permeability higher than 1.01 are refused[4]. This reflects on the production of these two months, which has been rather stable.

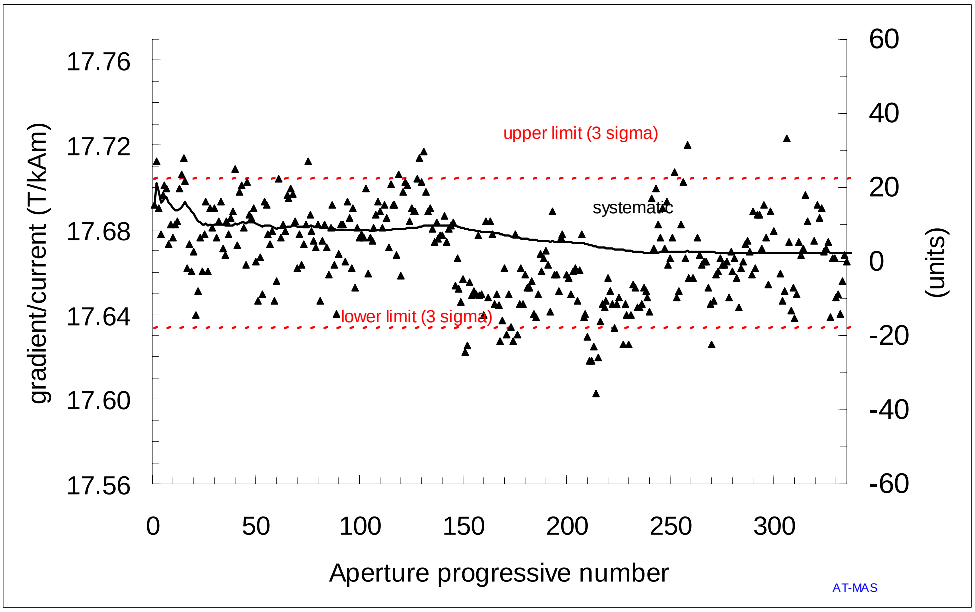

Fig. 7: Field gradient of the measured apertures (dots) and running average (solid lines, separated according to different cross-sections).

- The large spread observed in apertures (13 units) is confirmed by **cold mass** data, where it is around 13 units (see Fig. 8). Please note that 42 cold masses have cross-section 2.

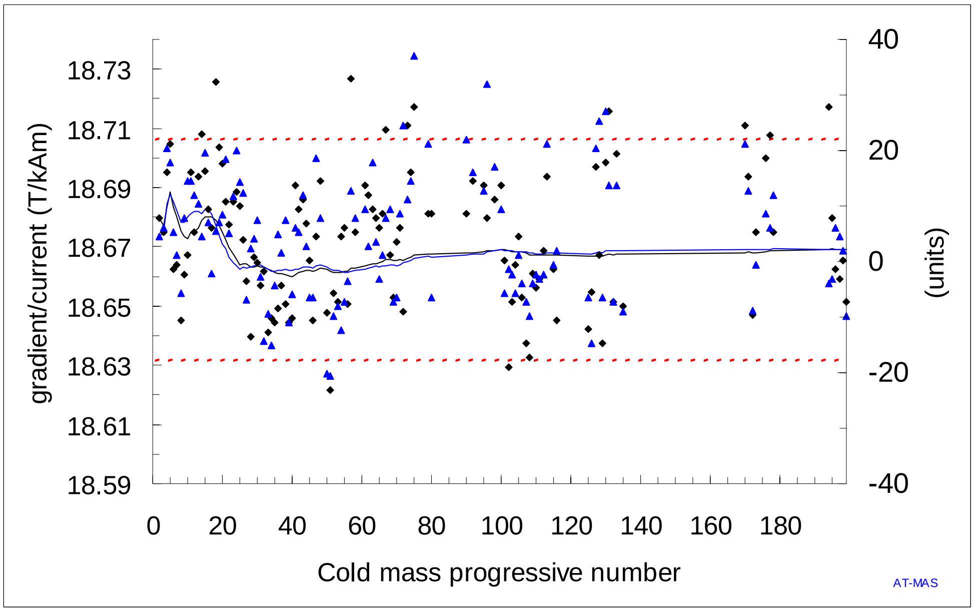

Fig. 8: Field gradient of the measured **cold masses** (black dots Aperture1, blue dots Aperture 2) and running average (solid line).

[4] F. Simon, private communication.

3.1.3 Trends in integrated field gradient

- The spread of the integrated field gradient (or focusing strength) is dominated by the spread in the field gradient, since the magnetic length is very stable, both in collared coils and in cold masses (see Fig. 9 and 10).

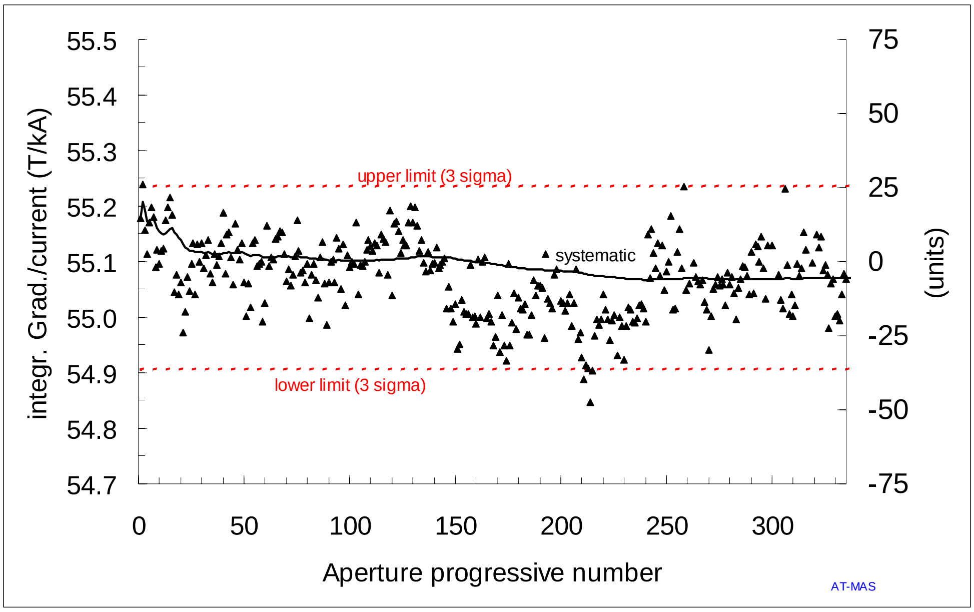

Fig. 9: Integrated gradient of the measured collared coils (dots) and running average (solid lines, separated according to different cross-sections).

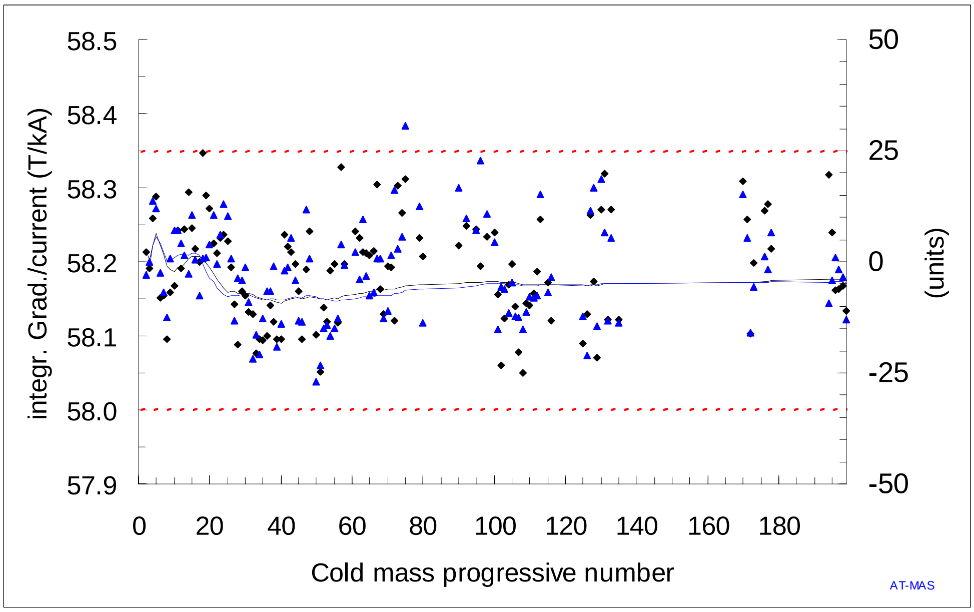

Fig. 10: Integrated field gradient of the measured **cold masses** (black dots Aperture1, blue dots Aperture 2) and running average (solid line).

3.2 Trends in allowed multipoles

- Systematic b6 has dropped from 5.5 units to about 3 units with the introduction of cross-section 2 (see Fig. 11). In the production of these two months, we are still having a few magnets with rather low b6.

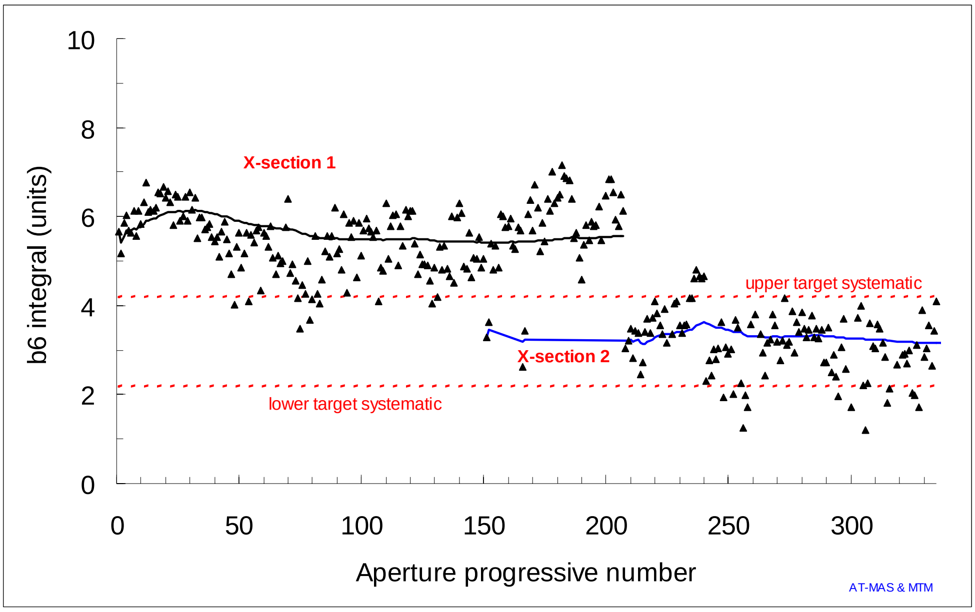

Fig. 11: Integral b6 in the apertures (markers) running averages per cross-section (solid lines), and beam dynamics targets for the systematic (red lines) based on correlations with 12 cryoquadrupoles.

- Systematic b10 is well within targets, and the impact of the cross-section change is small (0.2 units, see Fig. 12).

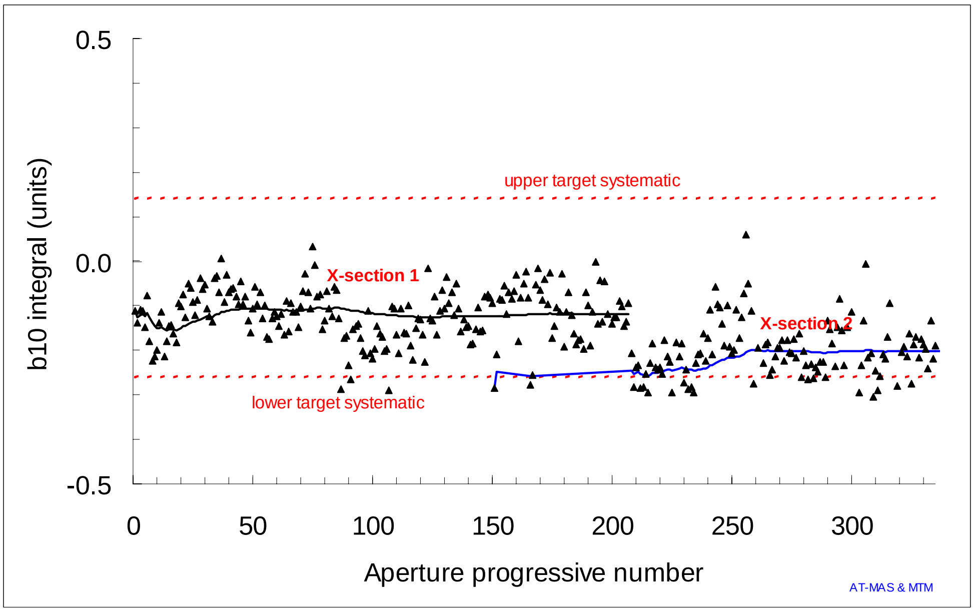

Fig. 12: Integral b10 in the apertures (markers) running averages per cross-section (solid lines), and beam dynamics targets for the systematic (red lines) based on correlations with 12 cryoquadrupoles.

3.3 Trends in non-allowed multipoles

3.3.1 Normals: b3, b4, b5, b7

- Systematic values of b3, b5 and b7 are close to zero as expected by the symmetry, and well within targets (see Figs. 13, 15 and 16). No trends are observed.
- The multipole b4 had a systematic component of about 0.5 units at the beginning of the production that is now disappearing (see Fig. 14).

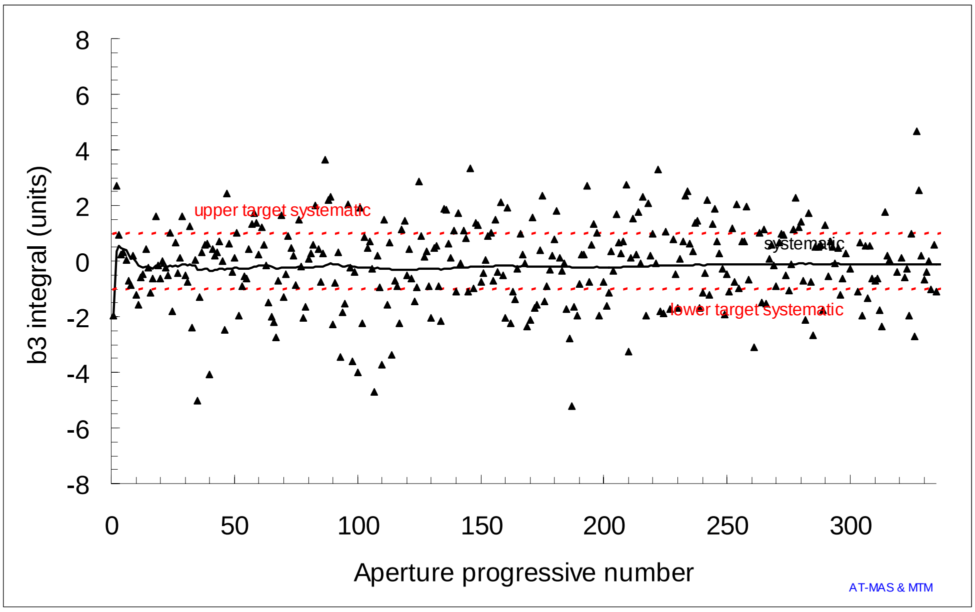

Fig. 13: Integral b3 in the apertures (markers), running average (solid line), and beam dynamics targets for the systematic (red dotted lines) based on correlations with 12 cryoquadrupoles.

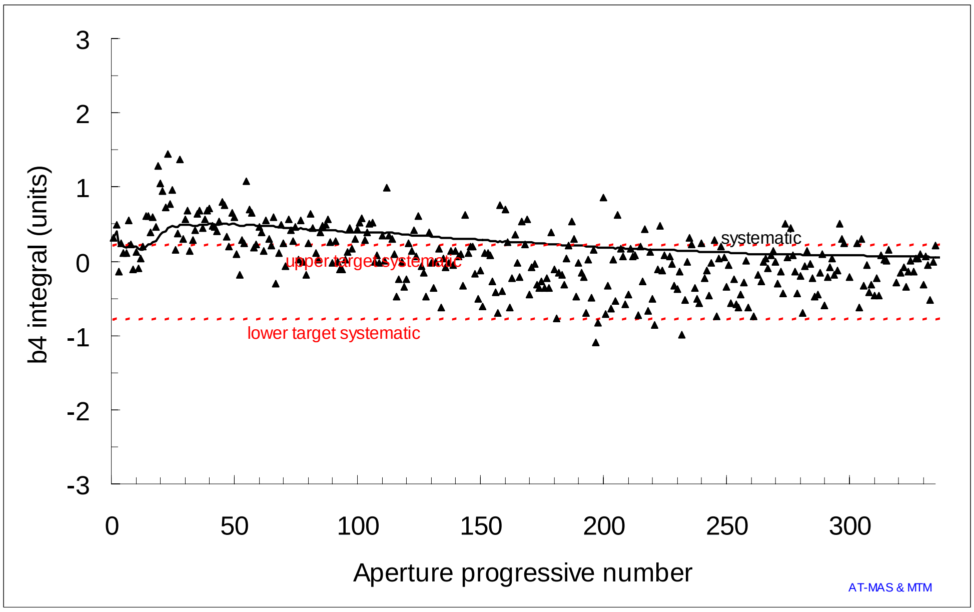

Fig. 14: Integral b4 in the apertures (markers), running average (solid line), and beam dynamics targets for the systematic (red dotted lines) based on correlations with 12 cryoquadrupoles.

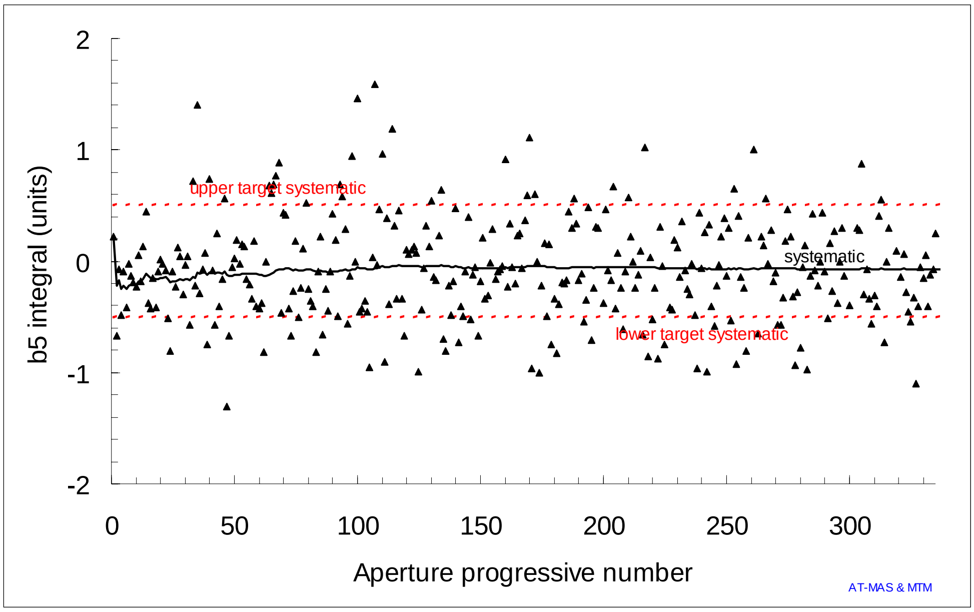

Fig. 15: Integral b5 in the apertures (markers), running average (solid line), and beam dynamics targets for the systematic (red dotted lines) based on correlations with 12 cryoquadrupoles.

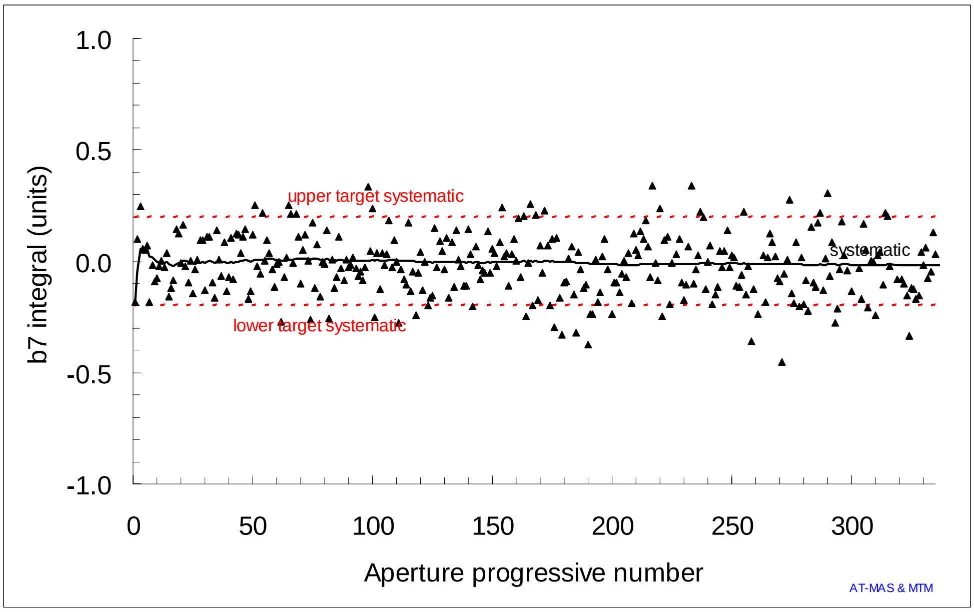

Fig. 16: Integral b7 in the apertures (markers), running average (solid line), and beam dynamics targets for the systematic (red dotted lines) based on correlations with 12 cryoquadrupoles.

3.3.2 Skews: a3, a4, a5, a6

- Systematic values of a3, a5 and a5 are close to zero as expected by the symmetry, and well within targets (see Figs. 17-19). No trends are observed.
- The multipole a6 has a systematic component of about 0.5 units since the beginning of the production (see Fig. 20). This unexplained component, which has trends along the production, is not critical for beam dynamics.

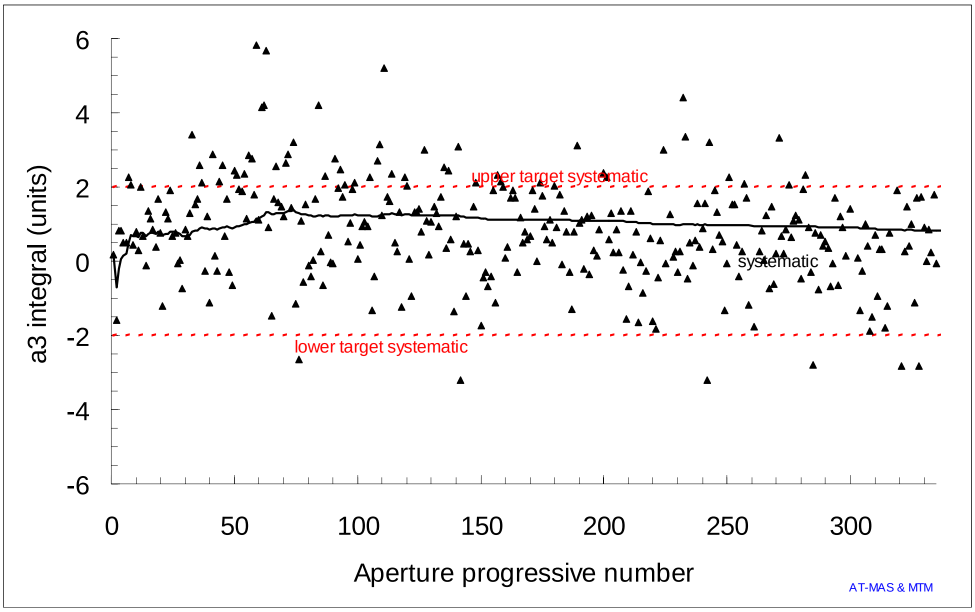

Fig. 17: Integral a3 in the apertures (markers), running average (solid line), and beam dynamics targets for the systematic (red dotted lines) based on correlations with 12 cryoquadrupoles.

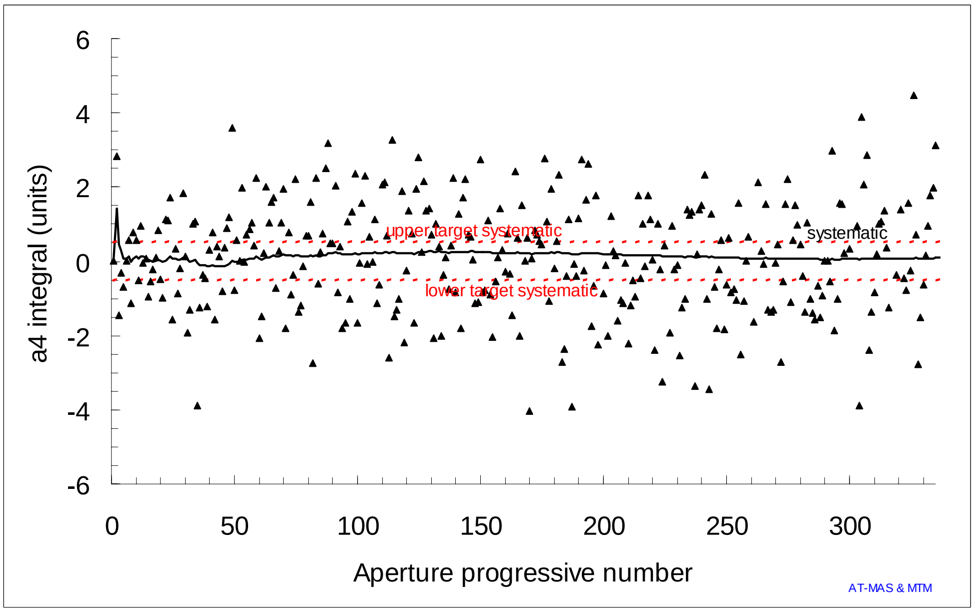

Fig. 18: Integral a4 in the apertures (markers), running average (solid line), and beam dynamics targets for the systematic (red dotted lines) based on correlations with 12 cryoquadrupoles.

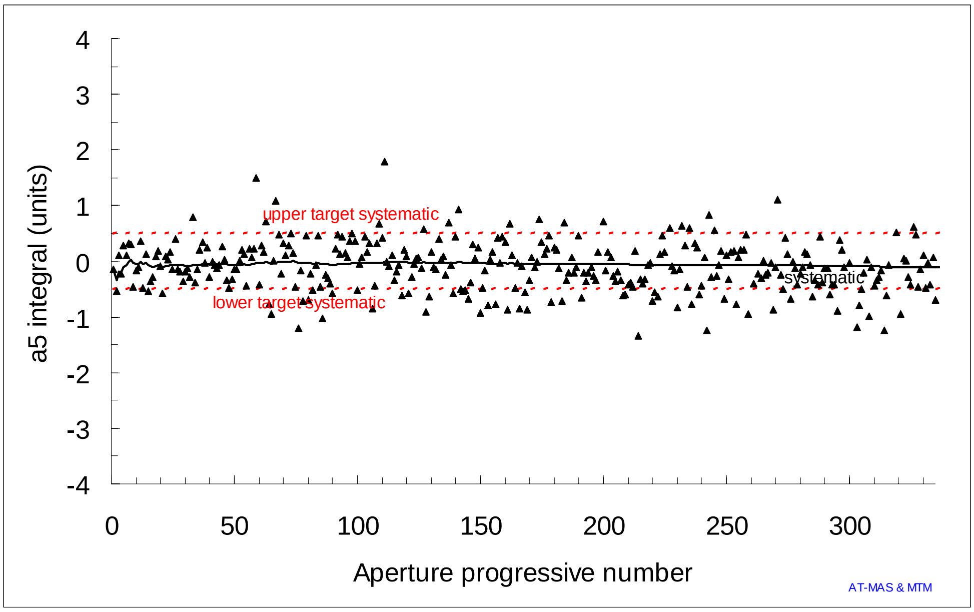

Fig. 19: Integral a5 in the apertures (markers), running average (solid line), and beam dynamics targets for the systematic (red dotted lines) based on correlations with 12 cryoquadrupoles.

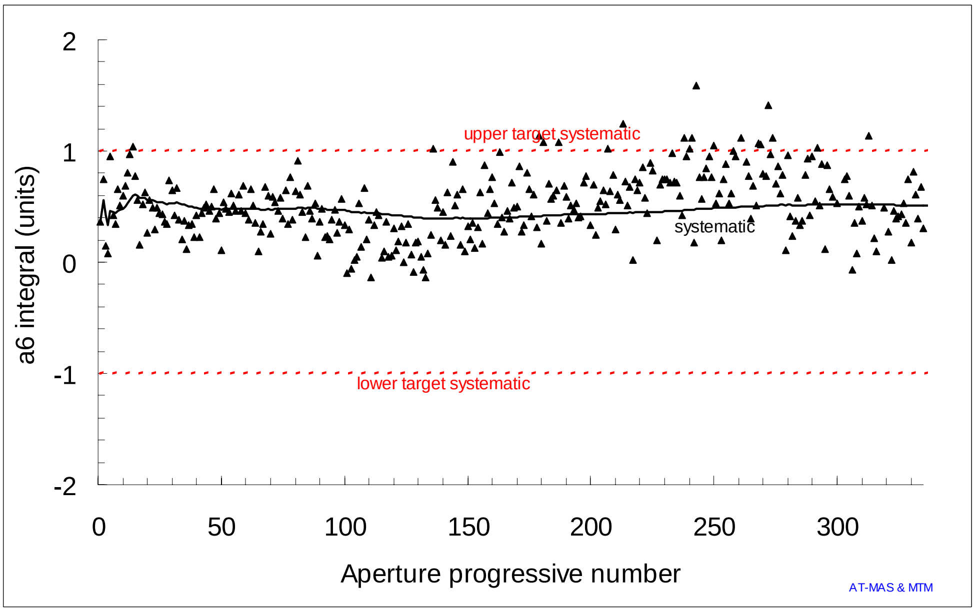

Fig. 20: Integral a6 in the apertures (markers), running average (solid line), and beam dynamics targets for the systematic (red dotted lines) based on correlations with 12 cryoquadrupoles.

3.4 Trends in correlations to measurements at 1.9 K

We give a trend plot for correlations for the two main critical values, namely the integrated field gradient and b6. Instead of giving the standard 'warm versus cold' plot, we give the measured offset, i.e. the difference between measurements at 1.9 K (at injection or high field), and at room temperature (at 12.5 A) versus the aperture progressive number. This gives an idea of the sampling that is being performed at 1.9 K (last aperture tested at 1.9 K is 154[5], i.e. there is a delay of 90 equivalent quadrupoles between room temperature measurements of collared coil and test at 1.9 K), and allows to detecting trends in correlations along the production.

- Integrated field gradient: we present data of 10 measured quadrupoles. We plot the difference between the integrated gradient at room temperature and at high field. Both the cases of the collared coil and of the cold mass measurement are shown.
    - The offset between apertures at room temperature (i.e., without iron yoke) and quadrupoles at 1.9 K is shown in Fig. 21. In the right part, values are given in units relative to the nominal value of 58.5 T/kA.m. The average value of 3.3 T/kA.m is mainly due to the field increase due to the iron yoke (approximately 5%). Two apertures, corresponding to magnet 004, have a rather low offset compared to the other ones (around 3.15 T/kA.m, see Fig. 21). Indeed, the analysis of data at 1.9 K does not present any anomalies justifying a rejection of the measurement[6]. The magnets measured in the last two months are in line with previous measurements (see dots around aperture 150, Fig. 22). The overall spread of the offset in the gradient is 15 units, and becomes 10 units when the data of 004 are not taken in to account.

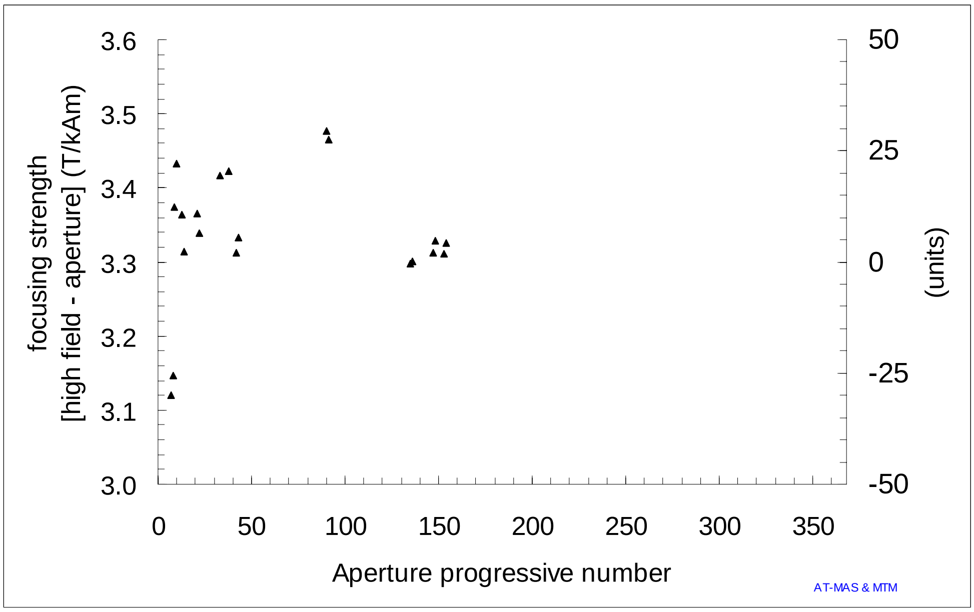

Fig. 21: Difference between focusing strength between high field at 1.9 K and collared coil at room temperature versus aperture progressive number

[5] Please note that measurements of cold masses at block4 are not included in this analysis.
[6] S. Sanfilippo, private communication

- The offset between cold masses (i.e., with iron yoke) at room temperature and quadrupoles at 1.9 K is shown in Fig. 22. In the right part, values are given in units relative to the nominal value of 58.5 T/kA. The average value of 0.25 T/kA.m (i.e., approximately 0.4%) is mainly due to the field increase due to the thermal contraction. Also in this case, the data corresponding to magnet 004 are much lower than the other ones. The overall spread of the offset in the gradient is 14 units, and becomes 8 units when the data of 004 are not taken in to account.

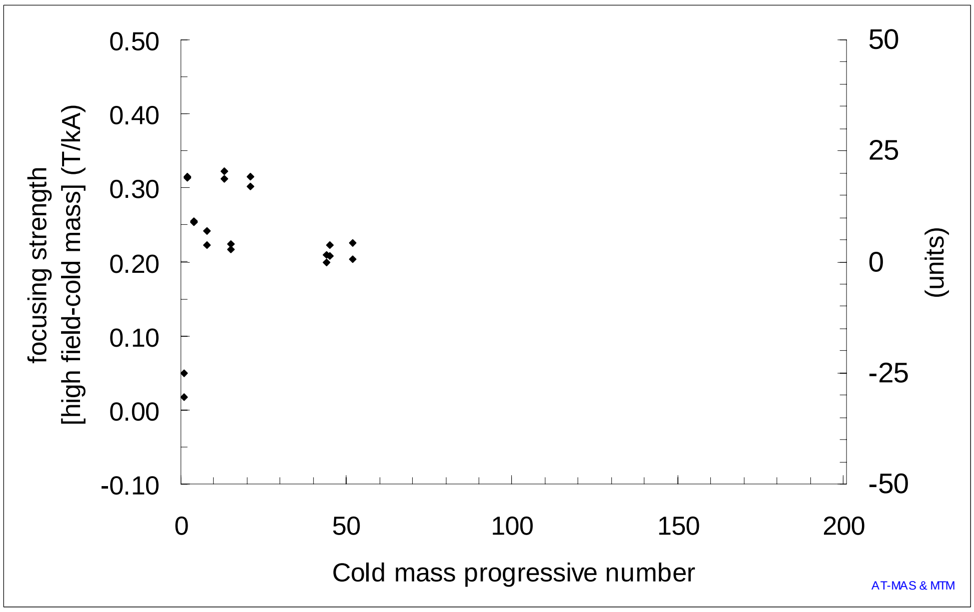

Fig. 22: Difference between integrated field gradient divided by current between high field at 1.9 K and collared coil at room temperature versus aperture progressive number

- Allowed multipole b6: over the 13 available measurements (26 apertures), we see a difference between injection and collared coil of -3.5 to –4.5 units. The most recent measurements (magnets 68, 71 and 74, corresponding to the six dots around aperture progressive number 150th in Fig. 23) show a small reduction of the offset. The average offset is –3.9 units, with a spread of 0.28 units (one sigma).

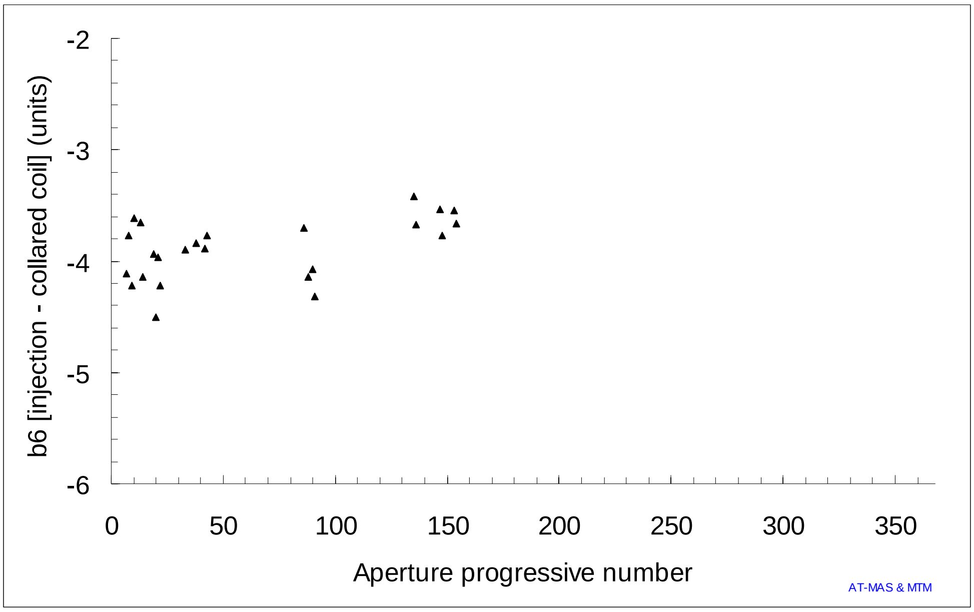

Fig. 23: Difference between integrated b6 between injection field at 1.9 K and collared coil at room temperature versus aperture progressive number

- <u>Not allowed multipole b4:</u> over the 13 available measurements (26 apertures), we see a unexplained feature of the offset, that for apertures 20 to 40 is not centred around zero. In the more recent production (from 70 onward), the offset is centred around zero as expected (see Fig. 24). The spread of the offset is similar to the spread of the measurements at room temperature (0.4 units), i.e. there is not correlation.

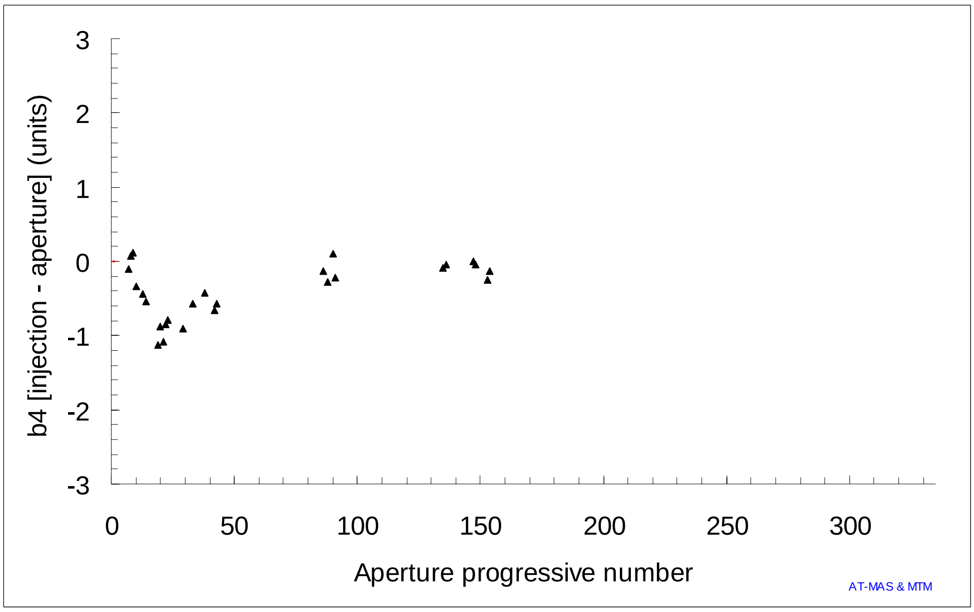

Fig. 24: Difference between integrated b4 between injection field at 1.9 K and collared coil at room temperature versus aperture progressive number

- <u>Not allowed multipole a6:</u> over the 13 available measurements (26 apertures), we see a very stable offset between warm and cold measurements, centred around zero (see Fig. 25). The spread of the offset (0.11 units) is much smaller than the spread observed in the apertures (0.28 units).

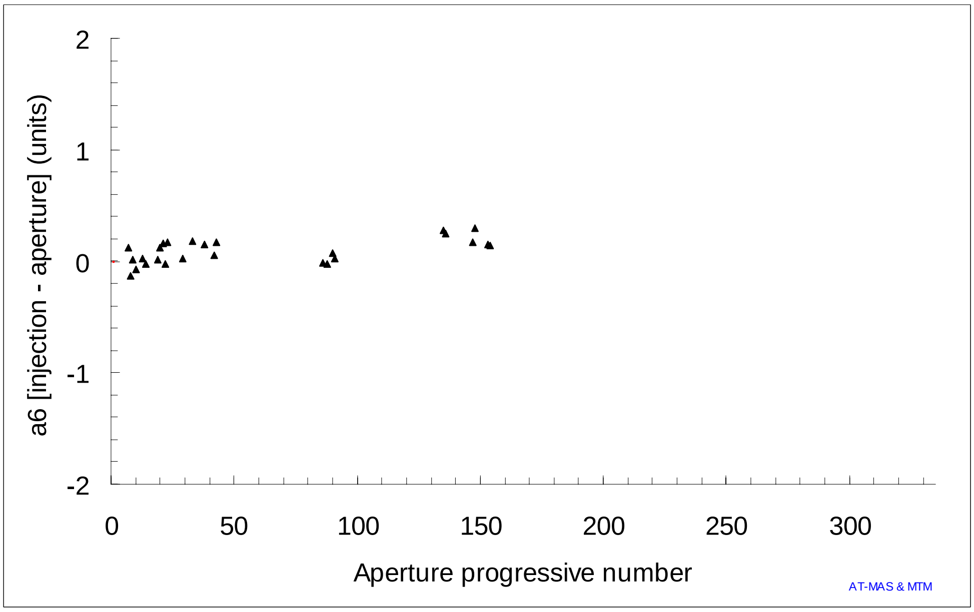

Fig. 25: Difference between integrated a6 between injection field at 1.9 K and collared coil at room temperature versus aperture progressive number

3.5 Trends in coil waviness

- The coil waviness estimated from the variation of the multipoles along the axis has drifted from initial values of 10 to 30 micron to 15 to 40 micron in the more recent production. The situation is stable in the last 150 apertures (see Fig. 24).

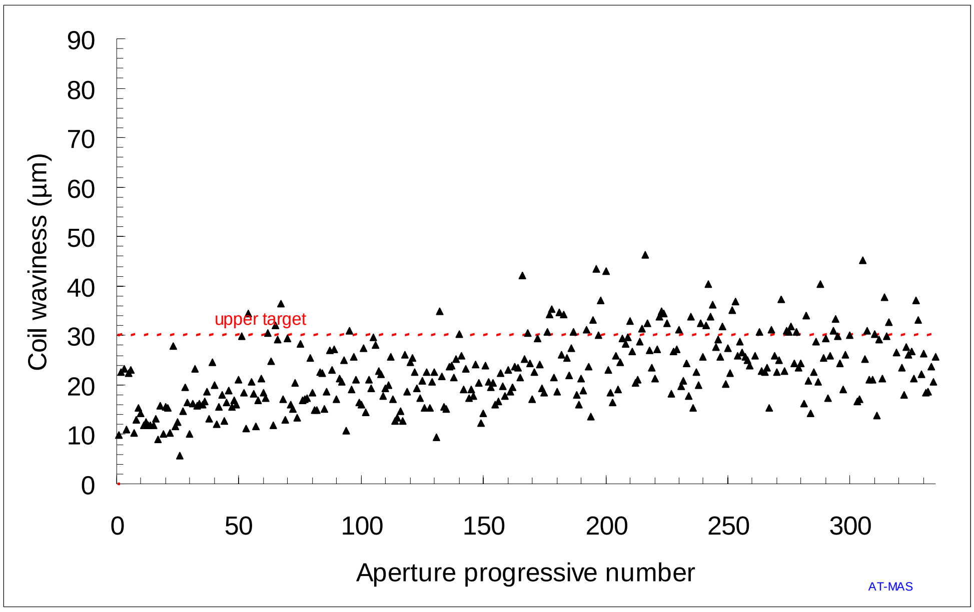

Fig. 24: Estimated coil waviness in the straight part of the measured collared coils (black dots: aperture 1, blue dots: aperture 2).

Acknowledgements

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